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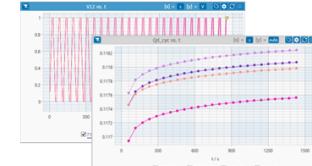


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Effects of Ceria Abrasive Particle Size Distribution below Wafer Surface on In-Wafer Uniformity during Chemical Mechanical Polishing Processing

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In this study, the abrasive size distribution of ceria-based slurry below wafer and its effect on in-wafer uniformity were examined. Based on our observation, the abrasive size varies depending on the location on the wafer. Hence process parameters such as pad surface morphology and slurry viscosity were thoroughly investigated to observe their effect on the distribution on the wafer surface. It was found that the small size particles were considerably reduced near the center location of the wafer surface during the pad lifetime with reduced slurry viscosity and high polishing pressure. Hence, the contact conditions and the characteristic of fluid should be simultaneously considered in order to obtain the stable in-wafer uniformity.

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Recently, the chemical mechanical polishing (CMP) industry is in the process to adopt new polishing abrasives by switching from the conventional silica-based slurry to ceria (CeO_2)-based slurry. CeO_2 slurries provide high removal rate and high selectivity with polymer additives and exhibit no slurry agglomeration with pad lifetime.¹⁻³ Control of the ceria abrasives size is vital to achieve better performance such as lower scratch level and higher material removal rate. In the past, many researchers proposed that scratch level was related to the particle size in slurry and suggested that smaller size abrasives should be utilized to reduce the scratch level.^{4,5} It was found that smaller ceria particles decreased the possibility to produce defects during polishing because they generate shallower structural deformation and diminished residual stress inside the lattice structure.⁶ However, while smaller ceria abrasive reduced scratch counts in the CMP process, the control of in-wafer uniformity deteriorated even with the polishing controller with advanced hardware.⁷ Hence, ceria-based slurry with smaller abrasive particles has diminished in-wafer uniformity more compared to silica-based slurry. This is due to the insufficient knowledge of the nature of polishing characteristics between pad and wafer according to abrasive size. Therefore, it is essential to study the relationship between ceria abrasive size distribution and polishing performance such as wafer removal rate and in-wafer uniformity in detail.⁸

Based on the basic polishing mechanism,⁸ the abrasive spatial distribution and its amount under wafer is a critical factor to control the material removal rate. Hence, in this work, the size distribution of ceria abrasive between wafer and pad was investigated in order to establish the relation between the abrasive size and in-wafer uniformity. Based on our results, guidelines for achieving the required high performance of the CMP process using the slurry with small ceria abrasive particles are provided.

Experimental

Experimental set-up.—In order to evaluate the abrasive size distribution below wafer during CMP process, we implemented few modifications to existing CMP equipment in the lab. As shown in the setup schematic in Fig. 1, we fixed the transparent glass plate with the same size of 8 in. wafer above the pad with two holes of 1 mm diameter aligned along the circumferential direction of the pad at the edge of 5 mm and center point. During the CMP process, the slurry flows into the space between the plate and pad, quitting through the holes, which is used to determine size distribution of ceria abrasive below the plate. Slurry flow rate and platen speed for

all the experiments was 100 ml/min and 90 rpm respectively, which is the same condition of standard CMP process. Polishing pressure was applied to exert 2, 4, and 6 psi by means of dead weight to evaluate the pressure effect on abrasive size variation under wafer.

Polisher.—Polishing was performed on 8 in. PE-TEOS wafer with commercial 8 in. polishing machine (MIRRA, AMAT Co.) under 4 psi head pressure for 60 s, which is the typical monitoring condition for ceria slurry CMP process. The platen and head rotation speeds were 90 and 100 rpm, respectively. In-wafer uniformity of each condition was measured with the same instrument.

Particle size measurement.—The scanning mobility particle sizer (SMPS, HCT Co.) was used to measure the size distribution of ceria abrasives in different locations under the wafer.⁹ In the previous research, we demonstrated the feasibility of SMPS to measure the particle or abrasive size with superior resolution for sub-100 nm particle size.^{6,10} When the slurry samples were diluted with 100 ml deionized (DI) water, the slurry transformed from colloidal state to aerosol-type slurry. The aerosol-type slurry through the differential mobility analyzer (DMA, HCT Co.) facilitates the measurement of the size of the abrasives which corresponds to the electrical mobility of each abrasive size.¹¹ Then, the condensation particle counter (CPC, HCT Co.) was used to measure the number of particles or particle concentration.

Ceria abrasives.—The experiments were carried out using four types of ceria slurries named as type A to D for ease of explanation. Size distribution of each ceria was measured by SMPS. Three of them viz. Type A, B, and C has uni-modal size distribution whereas type D has bi-modal size distribution, especially has lots of small size abrasives between 20 and 30 nm areas. However, each one of uni-modal type A, B, and C has different median particle size and size distribution as depicted in Fig. 2a: Type A has the particle size ranging from 40 to 300 nm with the peak at 70 nm; Type B from 50 to 350 nm with the peak at 80 nm; Type C from 65 to 400 nm with the peak at 90 nm. Type D slurry has bi-modal size distribution with the first peak between 20 and 30 nm and the second peak at around 100 nm. TEM images in Fig. 2b confirmed the distribution mode of uni- and bi-modal slurries. All types of slurry have the same ceria particles synthesized with the same technique, however, their size was controlled by milling process time with zirconia balls. Especially for Type D slurry, the milling process time has long term barrier than that of Type A, B, and C slurries. Thus there are more chances to have smaller particles to form bi-modal distribution. The effect of slurry viscosity on slurry size distribution is examined by modifying the slurry viscosity with the anionic polymer additive

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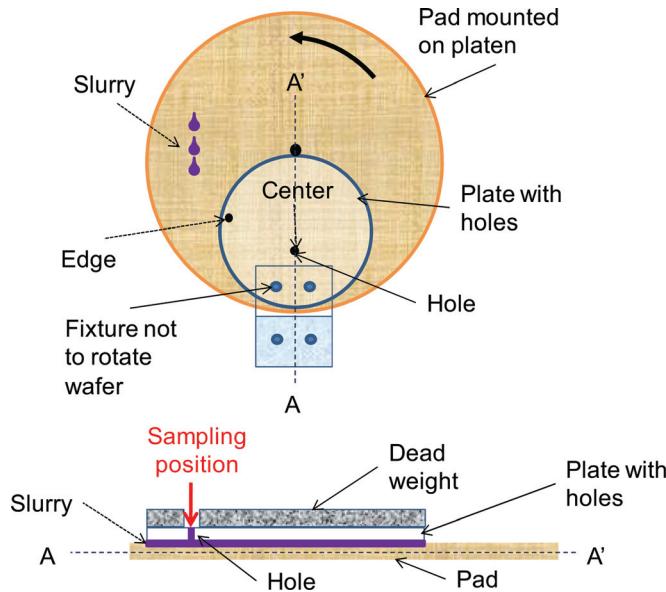


Figure 1. (Color online) Experimental setup and schematic diagram of both top and side view of the polishing apparatus to sample slurry according to different wafer locations.

(poly-acrylic acid). The additive amount of 0, 0.3 and 0.5% make slurry viscosity of 1.33, 2.40 and 3.82 cps for Type A slurry and 1.21, 2.25 and 3.60 cps for Type D slurry, respectively. pH of slurries are neutralized to seven, approximately, to prevent variation of electrical charge of ceria surface by different pH. Poly-acrylic acid is a famous agent for STI (shallow trench isolation) CMP process to

get $\text{SiO}_2/\text{Si}_3\text{N}_4$ removal selectivity. In the view point of selectivity, previous studies mainly focused on its electrical and adsorption behavior onto the film surfaces.^{12,13} However, effect of polymer additive on abrasive size distribution which influences CMP performance is focused in this study.

Results and Discussion

The particle size distributions of each slurry type at both center and edge locations of the transparent plate using an unused polishing pad are measured and compared with the original distribution of corresponding slurry type obtained prior to experiments as shown in the Figs. 3a–3d. In the case of the uni-modal size distribution i.e., Type A, B, and C, the amount of small size particles at the center was found to be significantly reduced, however the size distribution at the edge was unaltered. In the case of the bi-modal size distribution i.e. Type D, a similar trend was observed but the entire particle count at the center location was greatly reduced. It can be assumed that the variation in the particle size distribution for different locations undoubtedly have an effect on in-wafer uniformity and removal rate during polishing of a wafer. However, according to previous studies, removal rate of oxide was strongly related to the number of abrasive particles in slurry.^{14–16} Hence, it is critical to investigate factors that contribute to the variation of particle distribution at different wafer locations. Since pad surface morphology and slurry viscosity were main factors that affect the particle distribution,¹⁷ the effect of CMP parameters such as pad surface morphology and slurry viscosity was investigated to obtain the uniform abrasive size distribution irrespective of wafer location. Also, we examined the size distribution effect of polishing pressure. In this study, Type A and D slurries were utilized for the experiments to observe the similar effect. Type A represented a uni-modal size

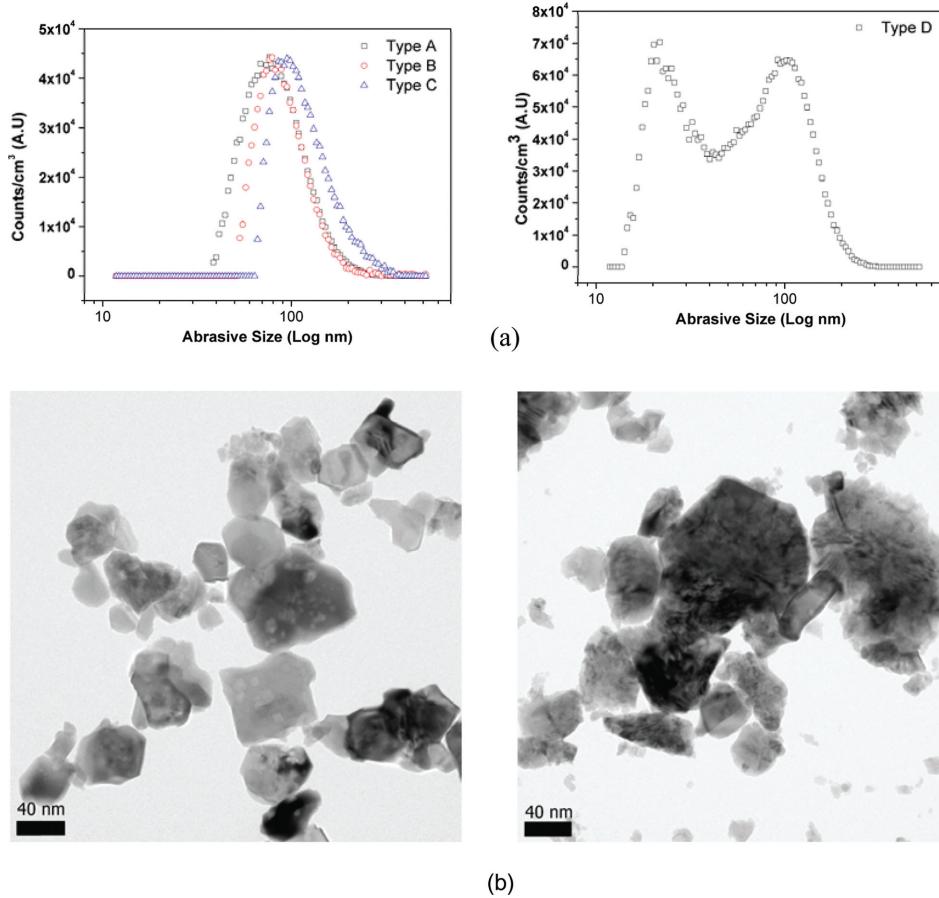


Figure 2. (Color online) Four different kinds of ceria abrasive used in this experimental. (a) Size distribution of each ceria measured by scanning mobility particle sizer (SMPS) and (b) its TEM images showing uni- (left) and bi-modal (right) distribution (Type A and D).

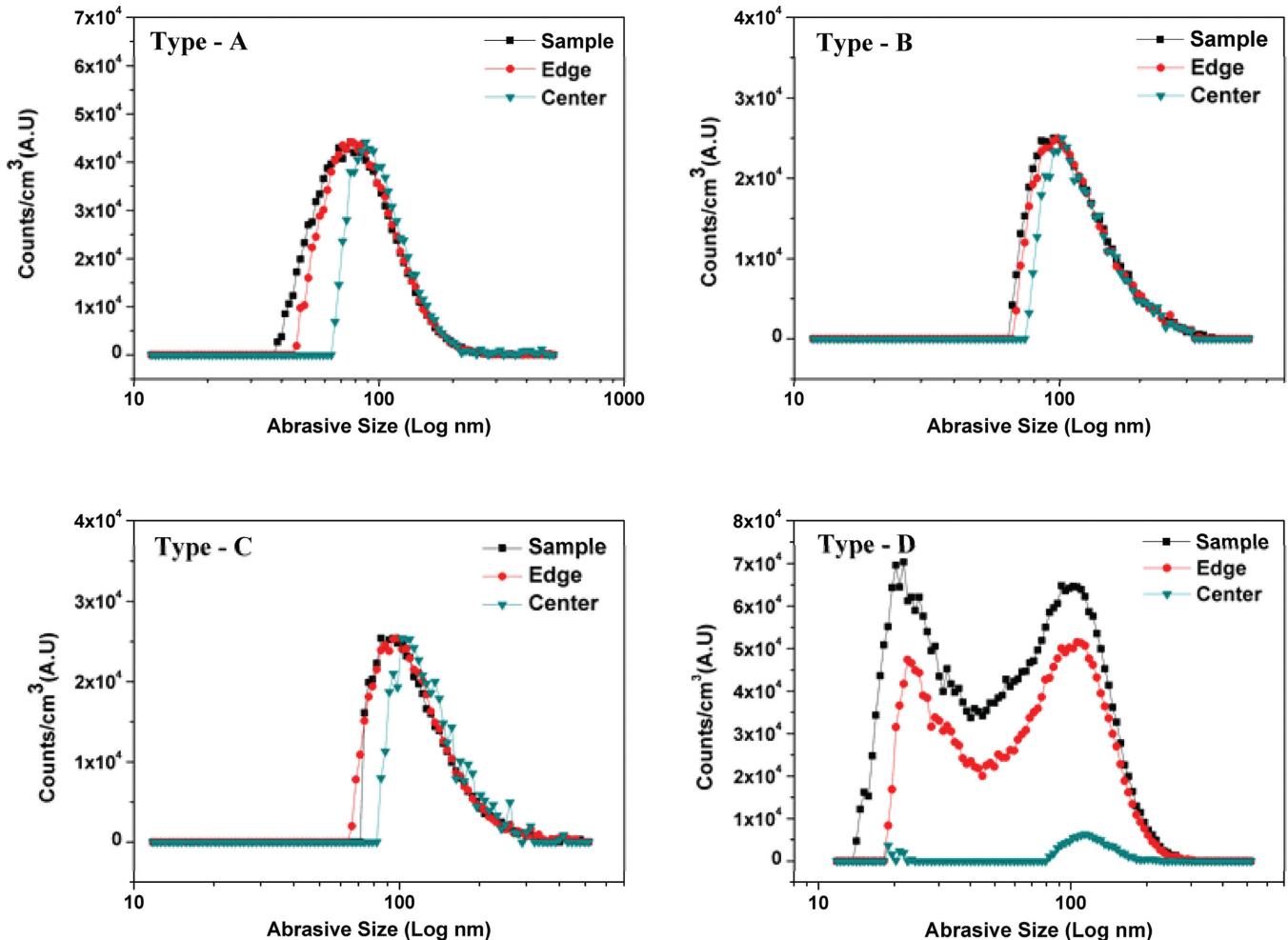


Figure 3. (Color online) Change in abrasive size distribution on different locations under wafer according to each abrasive type.

distribution including particles from 40 to 65 nm, which were not observed in Type B and C, and exhibited a significant reduction of small particles at the center while Type D represented a bi-modal size distribution.

Effect of polishing pressure on size distribution.—Figure 4 presents the effect of pressure on abrasive size distribution of wafer center area in Type A and D slurries. The measurement samples were taken during polishing. As the abrasive size distribution of wafer edge location is similar to that of sample slurry, the slurry existence of wafer center area was only compared. For both slurries, the abrasives of smaller size were not found in the condition of the highest polishing pressure. It is seen that the condition of lower pressure is an effective method to keep the small ceria abrasive at the wafer center area. Also, as the polishing pressure increases, the amount of slurry abrasive decreases below wafer, this implies that the total amount of slurry is affected by polishing pressure.

Effect of pad morphology on size distribution.—The effect of pad morphology on size distribution was investigated by measuring the size distribution of the ceria particles in Type A and D slurries at the center for three different pads. Figure 5 shows the SEM surface images of unused IC1010 (Dow Chemical Co.) pad, IC1010 pad used for 24 h, and a pad with a smaller pore diameter and higher pore density. Average pore sizes are 25 and 20 μm for IC1010 pad and customized pad, respectively. Porosity was maintained for customized pad with more number of pores than IC1010 pad. With three different types of surface morphology, abrasive size distribution was analyzed. Figure 6 shows the change of abrasive size distri-

bution in the center for each pad surface. For both Type A and D slurries, abrasive size below 80 nm was not observed in used pad. In addition, the reduced amount of smaller size abrasives in the used pad is much larger than those in the unused pad. This implies that the abrasive amount at the wafer center location decreases with pad lifetime. This may have resulted from the deteriorated ability of the used pad to transfer the slurry into the center area due to its lowered surface roughness and diminished pores by glazing. Surface glazing increases frequency of severe contact between wafer and pad that results reduced number of flow channels where the abrasives can travel. In particular, the smaller particles are much more difficult to move through the micro fluidic channel, which has a smaller gap and narrower flow path, under wafer. On the other hand, pads with small pore size and high pore density exhibit little difference in size distribution between edge and center areas. The small contact area and numerous reservoirs facilitate the transfer of the slurry including the small size abrasives. Hence, a pad with the high pore density and good surface texture is needed to achieve uniform size distribution of slurry abrasive. It is well known that material removal rate is strongly driven by abrasive concentrations and abrasive size in oxide CMP.^{18,19} It is speculated that the deterioration of in-wafer uniformity by a used pad in the manufacturing site could be closely related with altered size distribution of the abrasive particles due to different surface morphology. Both pad structure and slurry abrasive size distribution should be considered to achieve the uniform removal rate throughout the wafer area.

The effect of slurry viscosity on particle size distribution.—The effect of slurry viscosity on slurry size distribution at the wafer

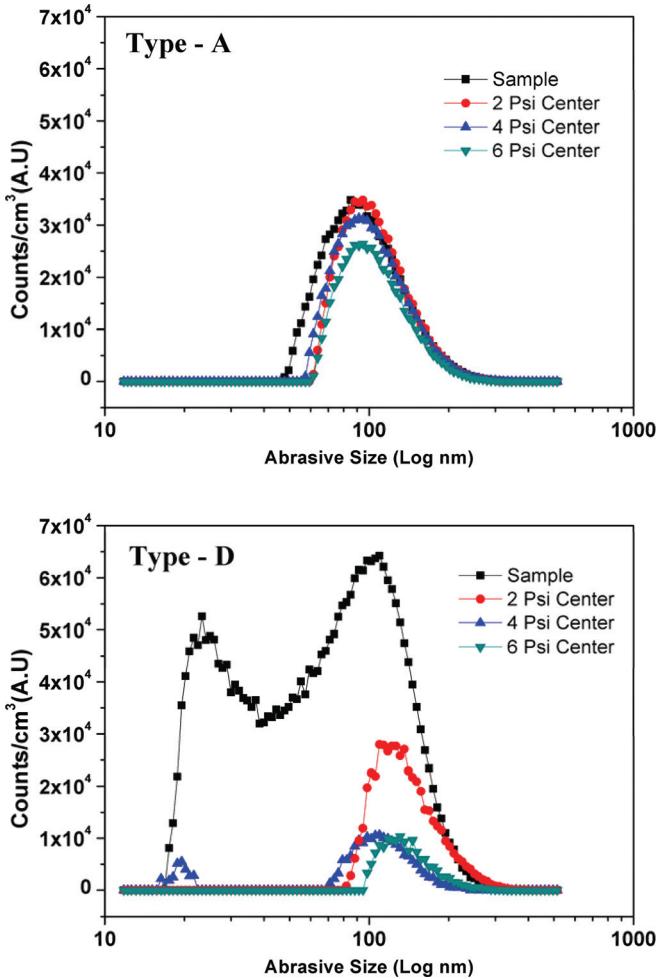


Figure 4. (Color online) Pressure effect of abrasive size distribution in (a) Type A and (b) Type D. The samples were taken during polishing.

center is examined by modifying the slurry viscosity with the anionic additive. As both slurries became more viscous with addition of the additive, smaller abrasive particles were observed and the amount of them increased at the same time as shown in Fig. 7. Type A slurry was gradually affected by the increased additives as shown in the Fig. 7a while Type D slurry exhibited significant increase in the particle account with the addition of additives as shown in the Fig. 7b. This suggests that the slurry with higher viscosity readily transfers abrasive particles to the wafer center area. The effect was more significant for particles below 100 nm for both slurry types.

The variation of abrasive size distribution under wafer, which is caused by the change in the pad surface morphology and the slurry viscosity, can be explained by considering forces applied to the particles in the micro-scale channel. Generally, it is understood that there exists the drag force (F_d), “van der Waals” force and double-layer electrostatic force (DLEF) on moving particles in the channel between wafer and pad surface.²⁰ If the drag force is dominant over DLEF induced by the zeta potential and the van der Waals force at the wall, moving or sliding distance of abrasive in the fluid channel is dependent on the drag force on the abrasive. The drag force²¹ is linearly proportional to the abrasive size and fluid viscosity as particle motion is lying in Stokes’ regime.

The set of forces acting on an abrasive particle can be divided into two regimes with respect to distance from wall to particle surface. Because DLEF and van der Waals force have very short range than wafer-pad gap height, which is several microns. Thus, most of abrasives are suspended outside of the electrical interaction region

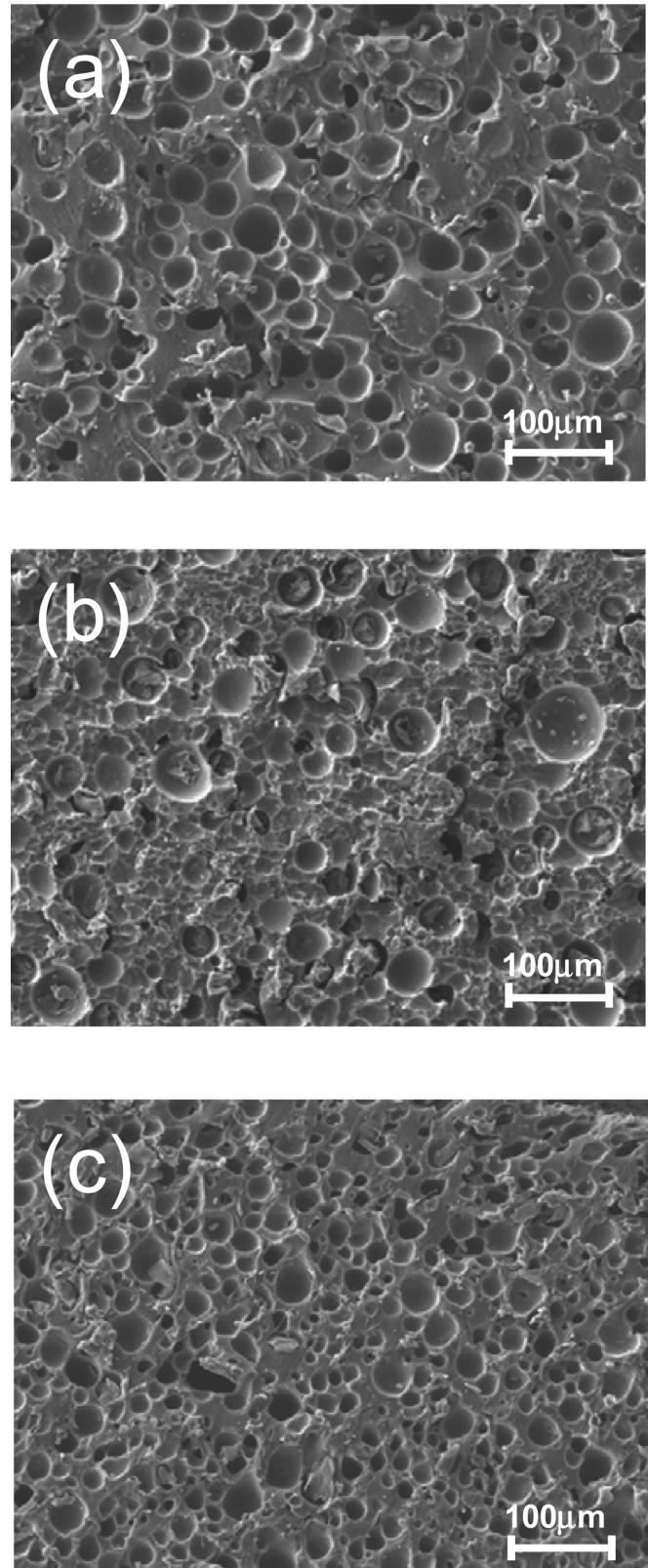


Figure 5. SEM images of (a) unused IC1010 pad, (b) used pad for 24 h and (c) pad with small size pores and high pore density.

at the wall and their motion is dominated by drag force. The drag force also resists the DLEF acting on the abrasive near wall. On the other hand, abrasives close enough to pad or wafer surface experience wall-particle interaction by electrical potential. However, the

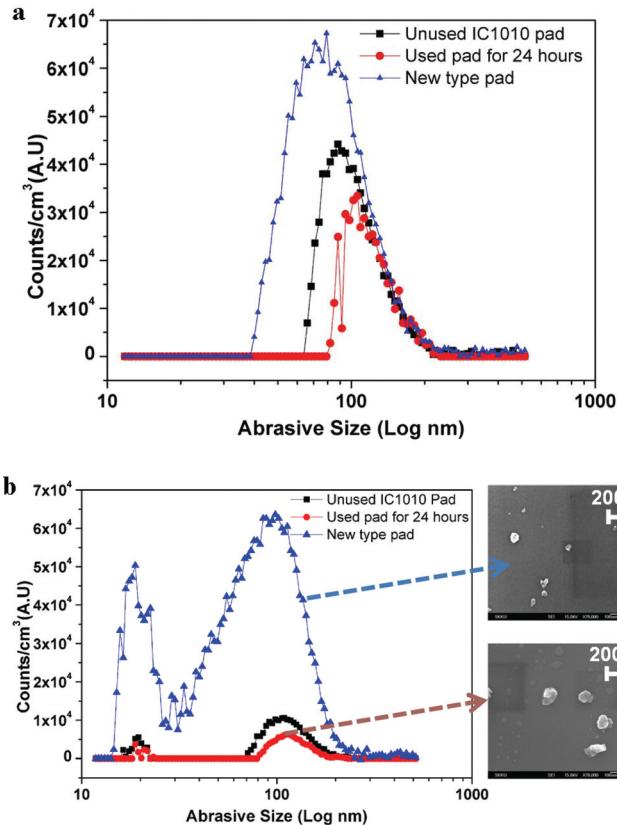


Figure 6. (Color online) Change of abrasive size distribution in (a) Type A slurry and (b) Type D slurry under wafer center according to pad surface morphology.

addition of polymer additive would result in formation of steric repulsive forces between wall and particle surface to enhance abrasive transport respect to fluid motion. This effect could be estimated by the result of zeta potentials (Zetasizer nano, Malvern Co.). We measured zeta potentials of Type A slurry for three different concentrations. The result indicated that zeta potential is negatively increased with higher PAA concentration. The zeta potentials are -46.3, -55.6, and -59.2 mV for the concentrations of 0, 0.3, and 0.5%, respectively. However, the change of zeta potential is dependent on ionic concentration but on expanded hydrodynamic diameter of the polymer chains because pH was not changed. Thus, only excessive amount of macromolecules attached to the particle surface are affect the zeta potential. This implies that dispersion stability of ceria particles is improved by the increase of PAA concentration, which results more ceria particles being transported into wafer center area. It is well reported that the PAA molecule is not well adsorbed by oxide surfaces, thus, we observed higher removal rate at the wafer center area for PE-TEOS oxide film by PAA adsorbed particles in our later experimental section.

Process conditions such as larger particles and high viscosity will induce a larger drag force on abrasives, which moves the particle a longer distance. Furthermore, excess amount of PAA molecule on the particle surface promotes particle transportation by repulsive force to the oxide surface. Hence, our experimental results are justified by the difference of drag force according to particle size and dispersion stability according to PAA concentration.

Relationship between abrasive size distribution and CMP performance.—To examine the relationship between change in abrasive size distribution and CMP performance, the removal rate of the PE-TEOS layer was measured for three different CMP conditions such as the conventional conditions of 0.3% additive and

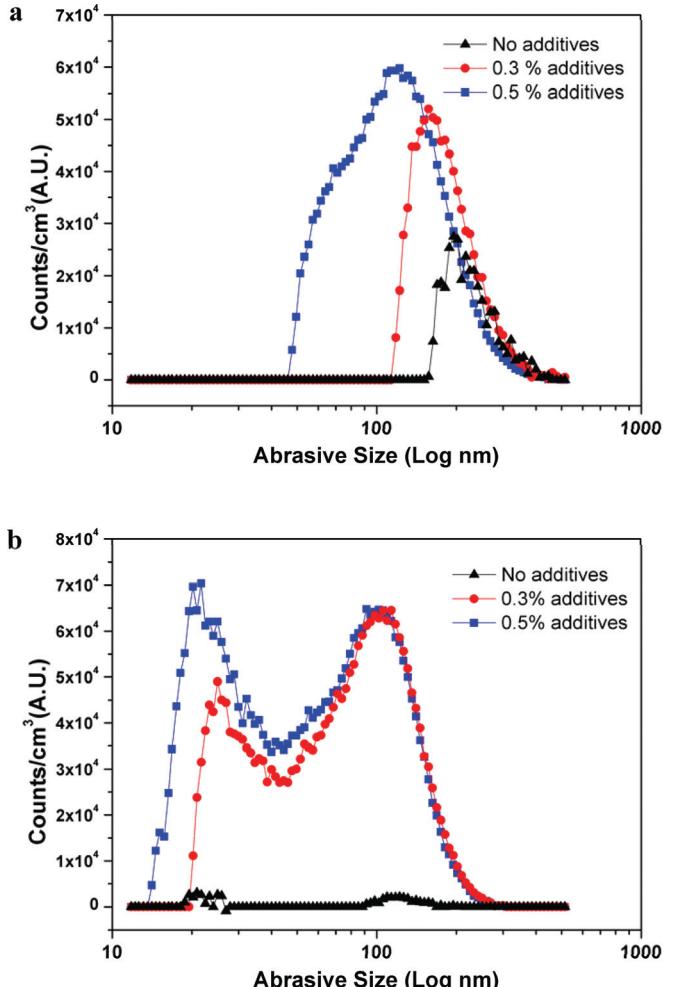


Figure 7. (Color online) Effect of slurry viscosity on abrasive size distribution in (a) Type A slurry and Type D slurry. The measurement samples were taken during polishing.

unused IC1010 pad, with the customized pad of a smaller pore diameter and higher pore density, and the slurry with 0.5% additive. Figure 8 shows the removal rate distribution of each experiment and Table I shows the within wafer non-uniformity (WIWNU). WIWNU was calculated using standard deviation uniformity of America Society of Testing Materials (ASTM)

$$\text{WIWNU} = \frac{\sigma_{RR}}{X_{avg}} \times 100 \quad [1]$$

where X_{avg} is the average removal rate and σ_{RR} is the standard deviation.

As can be seen in Fig. 8, it was confirmed that the increase of the removal rate at the center location resulted from the introduction of the customized pad and the slurry with increased viscosity for both Type A and D slurry when compared to the conventional conditions such as unused pad and 0.3% additive. In the case of Type A slurry, the smaller change in the size distribution and amount of abrasive particles lead to higher removal rate at the center than at the edge, so the WIWNU increased across the wafer. On the contrary, Type D slurry, which did not contain abrasive particles around 30 nm at the wafer center location under the conventional conditions, exhibited reduction in removal rate. When the slurry with larger content of the additive was used, in-wafer uniformity was largely improved due to the increase of material removal rate at the center location. In both cases, the increase of the removal rate at the center with the change

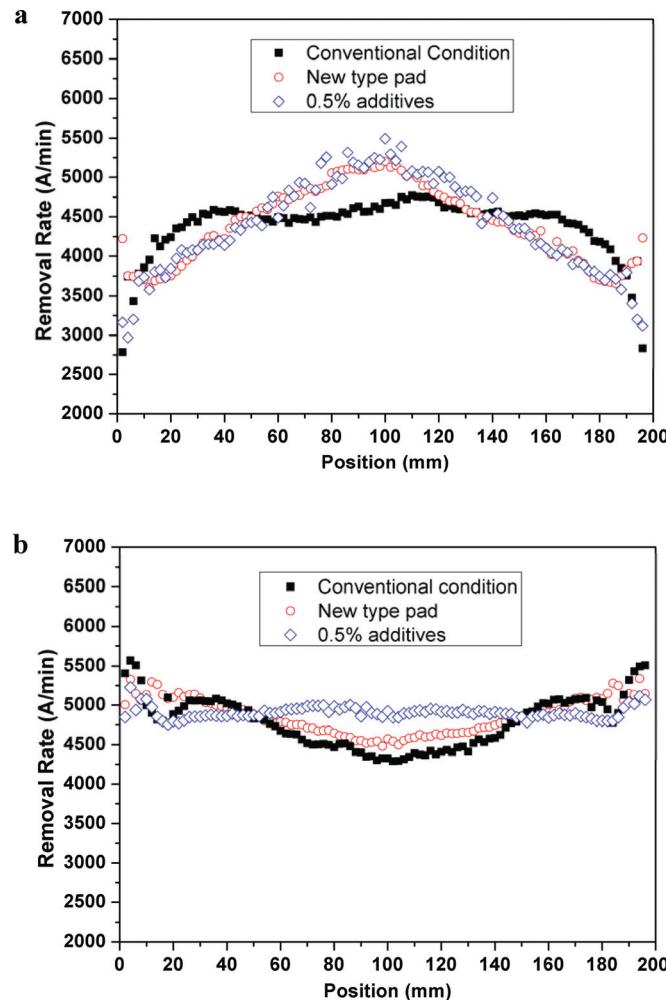


Figure 8. (Color online) PE-TEOS material removal rates in (a) Type A slurry and (b) Type D slurry.

in the polishing process are in good agreement with the measured particle size distributions previously, which showed increase of small abrasive particles at the center with the application of the customized pad and the increase of the additive amount. Thus, it is believed that the existence and the increase of the small size abrasive at the center location, which are resulted from the variation in pad morphology and slurry viscosity, are direct factors that increase CMP removal rate at the center location.

According to the material removal rate (MRR) model developed by Luo and Dornfeld, the relationship between the material removal rate and abrasive size distribution is written as²²

$$\text{MRR} = \frac{(x_{avg} + 3\sigma)^2}{x_{avg}^3} \quad [2]$$

where MRR is the material removal rate, x_{avg} is the average abrasive size and σ is the standard deviation of the abrasive size distribution. The decrease of the average abrasive size and the increase of the particle size distribution lead to higher material removal rate. This justifies our experimental results, where, the existence of small size abrasive at the center location due to the change in pad surface morphology and viscosity increases the standard deviation value and decrease the average size of abrasive, which confirms the increase of material removal rate at the center area.

Table I. WIWNU of PE-TEOS material removal rates test.

	Type A (%)	Type B (%)
Conventional condition	8.01	6.87
New type pad	10.83	4.70
0.5% additive	13.57	1.55

Conclusions

The effects of various process conditions such as pad surface morphology and slurry viscosity on abrasive size distribution under wafer were studied in this work to maintain the number of the small size abrasive particles regardless of wafer locations. The experimental results shows that, the condition of higher polishing pressure causes to reduce the amount of the smaller size and total abrasive size at the same time. Also, it was found that vanishing amounts of smaller size abrasive increased with pad lifetime and decreased with the pad with a smaller pore diameter and higher pore density. It is worth noting that the variation of the abrasive particle size distribution at the edge is insignificant while it is significant at the center. Thus, monitoring of the distribution at the wafer center location is crucial to obtain consistent size distribution of abrasive particles. In addition, it is found that the original abrasive size distribution larger can be maintained by controlling the viscosity of slurry. As a result, the in-wafer uniformity of a wafer can be optimized by considering process conditions such as the pad surface morphology and slurry viscosity, which affect the distribution of the small size abrasive particles.

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